A compact direct measurement method for relative positioning of KB mirrors nano-experimental apparatus based on grating interferometers

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I. Abstract

Positioning measurement is regraded as an effective way for the position compensation and feedback of nano-experimental apparatus. However, it usually suffers many restrictions from a complicated applied occasion of a typical performance beamline for next-generation synchrotron radiation light source. To deal with the problem, a compact direct measurement method based on grating interferometers is presented. The principle, configuration, experiment are designed and implemented for the verification of the feasibility. It performs a high resolution in orthogonal/lateral direction relative to laser beam, which can overcome an infeasible shortage of a typical interferometer for direct lateral positioning. So, it is used to positioning measurement & compensation between KB mirrors and nano-stages of a sample for the experiments of CDI, Bragg-CDI, Pytchograph, XPCS, etc. Compared with the existed methods, huge frame, two vacuum chambers restriction, multi-axis interferometer and benchmark relay are avoided for the compact system by using proposed method.

II. Introduction

Generally, as shown in Table 1, many complicated & multi-base & indirect metrology methods are used for relative position measurement or monitoring between optical component and sample. The big challenge is difficult to metrology them located in two separate chambers, especially for KB & sample.

Table.1 Brief summary of the metrological status

No.	Affiliations	Objectives	Two chambers	Scheme	Retro-reflection	Literatures
1	Diamond I14, UK	Bilateral, KB	YES	Typical FOI, Multi-base	Cylinder	Peach, Andrew, et al. "Engineering Challenges on the I14 Nanoprobe Beamline." Proc. MEDSI (2016)
2	SLS, Switzerland	Bilateral, ZP	NO	Differential LI, Common base	Hemisphere	Holler, M., et al. "An instrument for 3D x-ray nano-imaging." Review of Scientific Instruments 83.7 (2012): 073703. Holler, Mirko, and Jörg Raabe. "Error motion compensating tracking interferometer for the position measurement of objects with rotational degree of freedom." Optical Engineering 54.5 (2015): 054101.
3	PETRA-III P06, Germany	Bilateral, MLL	NO	Typical FOI, Common base	Sphere	Schropp, Andreas, et al. "PtyNAMi: ptychographic nano-analytical microscope." Journal of applied crystallography 53.4 (2020): 957-971.
4	NSLS-II HXN-MLL, US	Bilateral, MLL	NO	Typical FOI, Multi-base	Plane/regular	Yong S. Chu. Progress of the Hard X-ray Nanoprobe Beamline at NSLS-II and Early Science Experiments
5	NSLS-II SRX, US	Unilateral, KB	NO	Typical FOI, Multi-base	Plane/regular	Nazaretski, Evgeni, et al. "A new Kirkpatrick–Baez-based scanning microscope for the Submicron Resolution X-ray Spectroscopy (SRX) beamline at NSLS-II." JSR 29.5 (2022).
6	APS, US	Bilateral, ZP	NO	Typical FOI, Multi-base	Plane/regular	SRI2021
7	APS-U ISN, US	Bilateral, KB	YES	Typical FOI, Multi-base	Plane/regular	Steven P. Kearney†, Deming Shu, Tim Mooney, Barry Lai, Si Chen, and Jörg Maser, MECHANICAL DESIGN PROGRESS OF THE IN SITU NANOPROBE INSTRUMENT FOR APS-U*, MEDSI 2020
8	Sirius, Brazil	Unilateral, KB	YES	Typical FOI, Multi-base	Plane/regular	Geraldes, R. R., et al. "Design and Commissioning of the TARUMÃ Station at the CARNAÚBA Beamline at Sirius/LNLS." 11th Int. Conf. on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI2020), Chicago, IL, USA, virtual conference. 2021.

Therefore,

- **A metrological base scheme is a key, depends on the under test objectives.**
- **A common base is preferred, otherwise, multi-base often results in complicated and huge frame structure as a stable metrological base.**

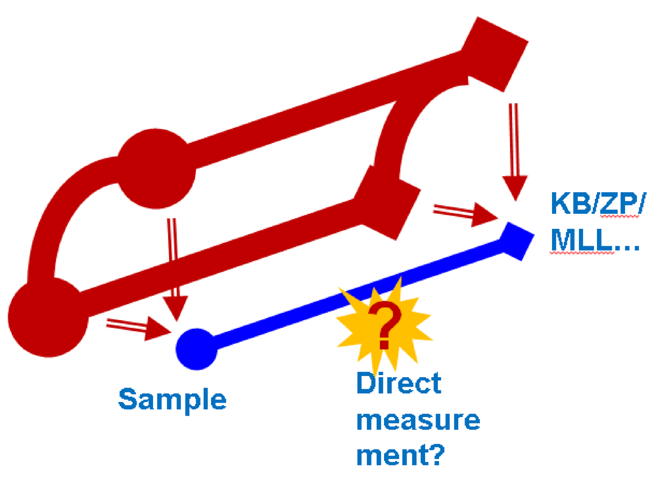

Fig.1 Lateral positioning between KB and sample

<u>Why hasn't widely adopted the compact common base scheme in the world? As shown in Fig. 1, the limitation of two individual chambers for direct lateral positioning is a big problem. Especially, larger KB make it much more serious than ZP or MLL etc.</u>

III. Principle & Configuration

A compact direct measurement method for positioning on grating interferometers is presented. The scheme is shown in Fig.2, in which two grating interferometers are employed for lateral relative positions between H-AKB/V-AKB and sample. It can overcome the problem of the lateral insensitive of a typical interferometer.

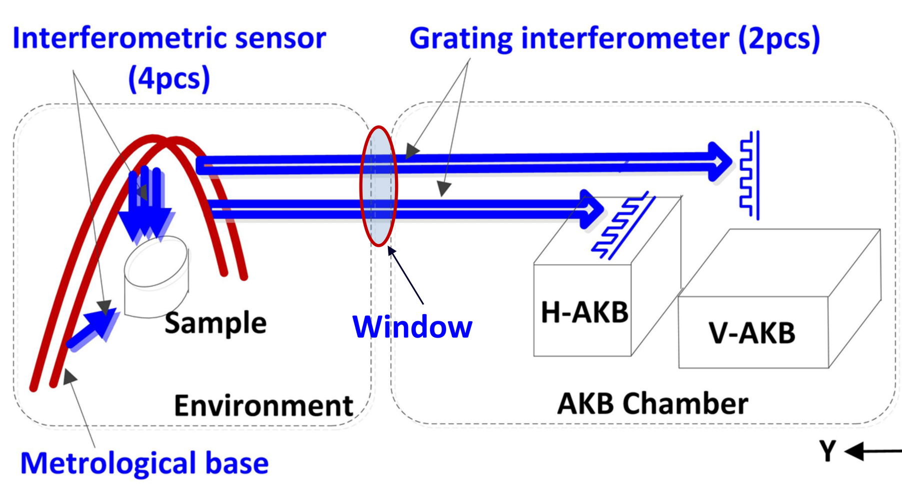

Fig.2 Metrology scheme of proposal method for Hard X-ray Coherent Scattering Beamline (HXCS) at HEPS

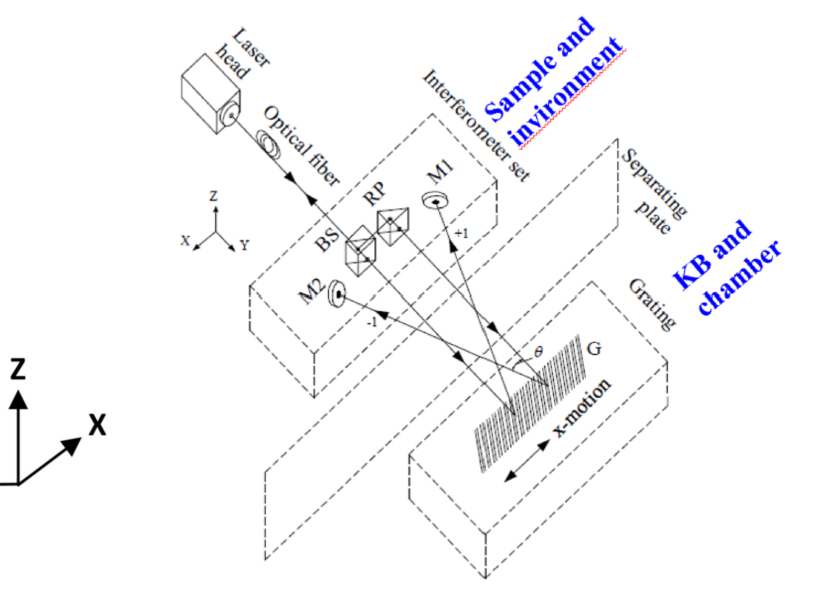

Fig.3 Principle configuration of the direct measurement

The principle & configuration of the direct measurement method is shown in Fig. 3. And the mathematical formula can be derived [1-3]:

$$s = \int_0^T V \cdot dt = \frac{d}{4} \cdot \int_0^T \Delta f \cdot dt$$

IV. Error analysis

- ☐ **Errors of several impact factors are considered and analyzed, as show in the Table 2.**
- ☐ **In order to guarantee the accuracy of the method, it can be calibrated in off-line by the temporary sensors or typical interferometers, as shown in Fig. 4.**

Table 2 Error items

Impact factorc	Values	HKB Error (nm)	VKB Error (nm)
Sensor Rotation Error	25μrad	<0.01	0.26
Engrating density error*	1%	<1	
Abbe error		0.45	<0.10
Mirror shape error	0.3nm	0.61	2.15
Total error		**<2nm**	**<3nm**

*Movement distance is set to 1 μm.

When the relative position between the sensors and grating changes, parameters k_m should be recalibrated.

- The temporary sensors Cx and Cy are used to obtain the movement distances of HKB which are the input parameters of calibration.

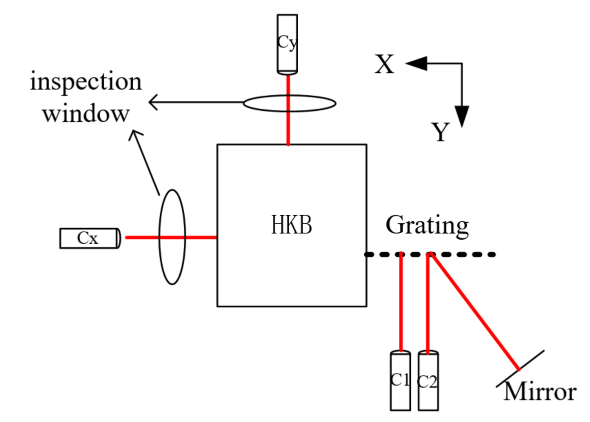

Fig. 4 Schematic diagram of calibration

V. Experimental verification

- ☐ **Experimental verifications for principle is implemented as shown in Fig. 6, Fig. 8 and Fig. 9. GI experimental system is home-made based on the FOI of Attocube IDS3010 and SmarAct respectively (GI-I and GI-S). Tests are implemented by respectively using GI-I and GI-S**
- ☐ **Results of the slopes (k) by curve fitting: 0.437 @GI-I, 0.434 @GI-S, agree with theoretical k=λ/d=1550/(1e6/300)=0.465, as shown in Fig. 5 Fig. 7.**

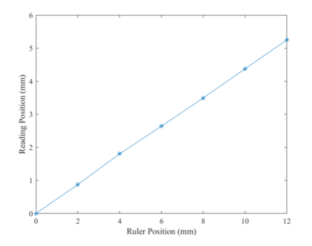

Fig. 5 Test curves of readout using GI-I relative to nominal position (ruler)

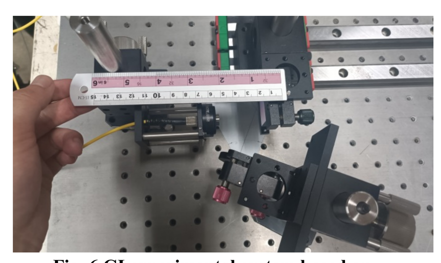

Fig .6 GI experimental system based on ID3010 (GI-I)

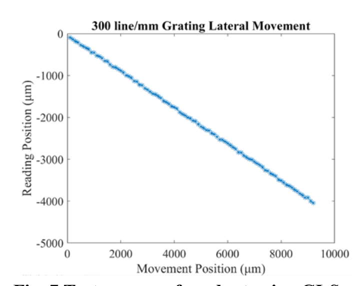

Fig. 7 Test curves of readout using GI-S relative to nominal position (PI stage)

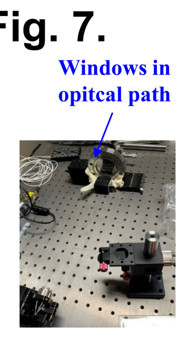

Fig. 8 Test for impact of the optical window

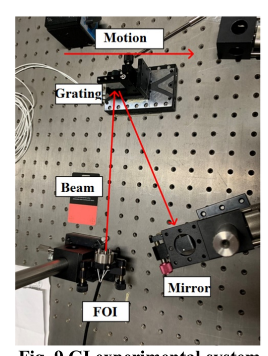

Fig. 9 GI experimental system based on SmarAct FOI (GI-S)

VI. Conclusions

- ☐ **A compact direct measurement method is presented. And it is proved feasible by experimental and theoretical verifications.**
- ☐ **The method has also up to the level of nm resolution as similar as the typical interferometer, which also features the characteristics of non-contact, real-time, and high-accuracy.**

1. S. Tang, Z. Wang, J. Gao, J. Guo, "Measurement method for roll angular displacement with a high resolution by using diffraction gratings and a heterodyne interferometer", Rev. Sci. Instrum., 85, 045110, 2014
2. S. Tang, M..Li, H. Liang, W. Sheng, J. Yang, "High-Accuracy Small Roll Angle Measurement Method Based on Dual-Grating Diffraction Heterodyne Interferometer", Proc. Mechanical Eng. Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI2018), Paris, France 25 th -29th, June. 2018, 163-167
3. S. Tang, Z.Ren, Q. Han, W. Sheng, and M. Li, "An improved differential-grating plane-mirror heterodyne interferometer for small roll angle measurement of a linear motion", Rev. Sci. Instrum. 91, 045113, 2020